

## Techniques for the Installation of Internal Fiber Optic Instrumentation on an 11-Inch Hybrid Motor Test Bed

Michael Cornelius  
Ziba Smartt  
Vaughn Henrie  
Mont Johnson  
ATK Thiokol Propulsion  
P.O. Box 9033  
Huntsville, Alabama 35812

### Abstract

The recent developments in Fabry-Pérot fiber optic instruments have resulted in accurate transducers with some of the physical characteristics required for use in obtaining internal data from solid rocket motors. These characteristics include small size, non-electrical excitation, and immunity to electro-magnetic interference. These transducers have not been previously utilized in this environment due to the high temperatures typically encountered. A series of tests were conducted using a 11-Inch Hybrid test bed to develop installation techniques that will allow the fiber optic instruments to survive and obtain data for a short period of time following the motor ignition. The installation methods developed during this test series have the potential to allow data to be acquired in the motor chamber, propellant bore, and nozzle during the ignition transient. These measurements would prove to be very useful in the characterization of current motor designs and provide insight into the requirements for further refinements. The process of developing these protective methods and the installation techniques used to apply them is summarized.

### Introduction

The extreme conditions found in the internal environment of a solid rocket motor (SRM) have made useful measurements of motor parameters and material properties difficult if not impossible to acquire. This has resulted in analysis and engineering which is based solely on theoretical parameters. This lack of complete understanding has been compensated with the use of conservative assumptions to provide additional margin against failure. More efficient rocket motors and design improvements could be considered if a database of test measurements could be developed. Fiber optic instruments have several physical attributes that make successful application in the SRM environment more feasible than their conventional counterparts. Fiber optic devices require a single fiber strand to provide light to the instrument and back to the signal processor. Conventional instruments typically require two to four wires for excitation voltage to the instrument and signal back to the processor. The presence of excitation voltage and direct copper paths in conventional instrumentation creates a safety issue when the physical properties of live propellant are measured. Since SRM propellant is sensitive to electrostatic discharges and applied voltages an unintentional ignition could result from an over voltage or stray voltage condition. This safety concern is not an issue

with fiber optic instruments that do not require excitation voltage and are isolated from stray voltages. Fiber optic instruments are typically much smaller in physical size and in mass when compared to other instrumentation options. This allows the impact to the measured environment and the potential for undesired debris in the burning propellant gases to be minimized.

The advantages of fiber optic instrumentation have not been leveraged in the SRM environment during previous testing due to several physical limitations that the test sequence described in this paper has attempted to overcome. The limitations of fiber optic instruments are the delicate nature of the glass or plastic fibers and the low melting temperature of the fiber material. The steady state temperature of the internal SRM environment is believed to be greater than 5,000 degrees Fahrenheit with chamber pressures approaching 1,000 pounds per square inch. These conditions make instrumentation installation, survivability, and lead wire egress difficult propositions. The test series described in this paper describes an attempt to develop protection schemes, installation methods, and egress techniques that will allow fiber optic instrumentation to be installed in the internal SRM environment and survive long enough to obtain meaningful measurements during the ignition transient. These methods were developed during a series of 11-Inch Hybrid SRM test motors that were built and tested at Marshall Space Flight Center in Huntsville, Alabama.

### **Materials and Methods**

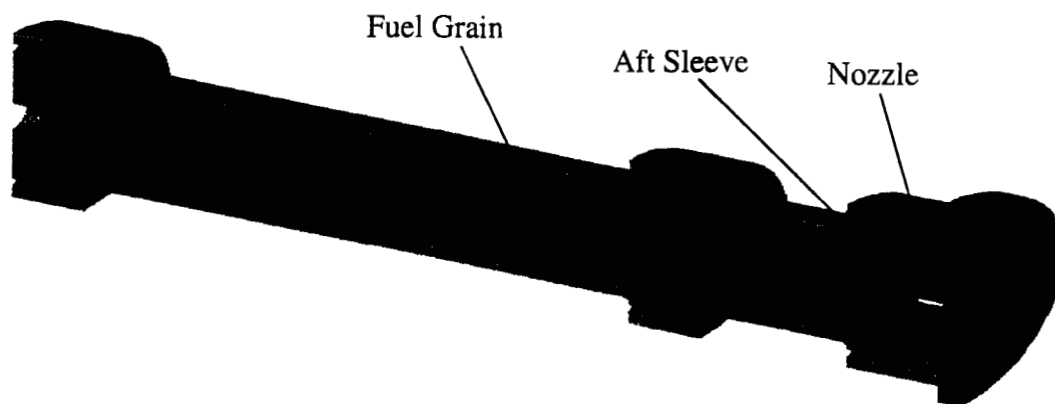
The instruments utilized during this test series were Fabry-Pérot interferometer based gages supplied by FISO technologies and are commercial off the shelf items. These gages are manufactured with two mirrored surfaces facing each other. The distance between the mirrors creates a small cavity which is wavelength modulated in exact accordance with the cavity length. The gage is designed in such a manner that the cavity length changes with the physical parameter being measured and results in a change in wavelength of the reflected light. This change in wavelength can be detected with appropriate signal conditioning and recorded using standard data acquisition systems. The primary objective of this testing was to apply these available gages in a unique way to acquire the desired material property data in the SRM environment. With instrumentation and signal conditioning commercially available the successful application of this technology was dependent on developing installation techniques that would allow the fiber optic gages to be installed internally in the SRM and protect them from the severe environment long enough to acquire the desired data.

Several materials were proposed as thermal barriers for the instruments and connecting fibers. A method of screening these materials and making side-by-side comparisons of their relative performance was needed to down select the most promising candidate materials. The Plasma Torch Test Bed (PTTB) at Marshall Space Flight Center (MSFC) was selected as a suitable test method that would allow several test specimens to be tested quickly and inexpensively. The PTTB consists of a Praxair plasma torch that is positioned using a robotic arm. The heat flux of the plasma is controlled with a feed back loop from a calibrated Medtherm heat flux gage, which allows the Praxair controller to adjust the parameters of the plasma generator until the desired heat flux level is obtained.

An Instron dynamic load tester allows the test specimen to be held or preloaded as specified by individual test parameters. A National Instruments data acquisition system allows the test data to be acquired and written into an Excel file for analysis. Test specimens for the thermal barrier candidates were fabricated by bonding two optical fibers between the candidate material and a carbon phenolic holder. A light source was applied to one end of the fibers and detected at the opposite end. The output of the detector was acquired by the data acquisition system. A 1000 Btu/ft<sup>2</sup> sec heat flux level was applied to the specimen by the plasma torch until the fibers failed and the signal through them was lost. This test method allowed the thermal protection properties of candidate materials to be tested relative to each other. This method was also used to evaluate the properties of several different adhesives used to bond the specimens together and the properties of various fiber types. This testing resulted in the initial selection of materials used during the first 11-Inch Hybrid tests. The materials and installation techniques used in the hot fire tests were modified and improved in an iterative fashion as the testing progressed.

A series of hybrid rocket motors were fired in a static test configuration in order to evaluate the performance of the installation and protection of the fiber optic instruments. The fuel and oxidizer are separated in a hybrid rocket motor, which differs from a conventional solid rocket motor where the fuel and oxidizer are bound together in the formulation of the solid propellant. The solid fuel of the hybrid motor is inert until a liquid or gaseous oxidizer is introduced and the motor is ignited. The installation of fiber optic instrumentation onto the hybrid fuel was much easier and safer because it was inert and the work could be performed in a standard lab environment that was not rated for explosives handling. Another feature of the hybrid motor is its ability to be throttled during its burn or shut down at a predetermined time. This feature enabled the test motor to run for a short duration, the motor shut down, and the instrumentation inspected before it was completely consumed as part of the motor firing. The flow of oxidizer to a hybrid motor can also be terminated by control feed back from various motor parameters such as motor over pressurization. This allowed the experimental installation techniques to be employed without risk to the integrity of the motor (Figure 1).

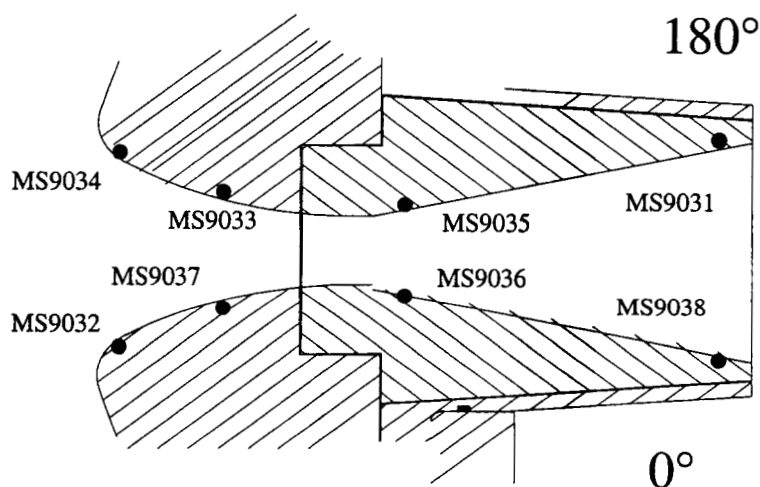
Four hybrid motor test firings were conducted with various instrumentation configurations. The performance of the installation and protection methods employed were evaluated after each firing and changes implemented on the subsequent firing in an attempt to increase the duration of usable data. The instrumentation installation on the first motor tests was restricted to the nozzle inlet and aft exit cone. The second test extended the instrumented region onto the aft sleeve where a single strain gage was installed on the inside wall and routed out through the nozzle. The nozzle and aft mixing chamber were also instrumented on the third test but the test region was extended onto aft edge of the aft fuel grain. Test four extended the instrumentation further forward into the aft fuel grain while continuing to test protection methods in the aft mixing chamber and on the nozzle.



**Figure 1 11-Inch Hybrid Motor Overview**

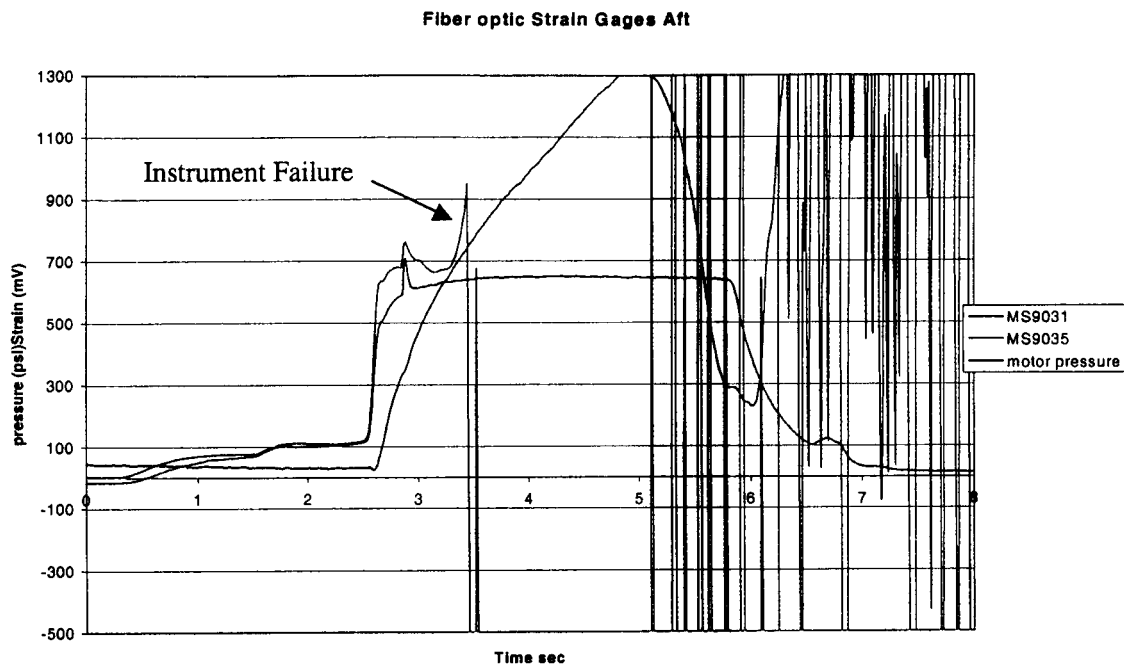
### **Results and Discussion**

**Test One:** The first motor in the series tested two protective straps in the nozzle. Each strap covered four strain sensors, two forward and two aft of the throat, for a total of eight sensors. The first strap, located at 0 degrees, was a proprietary formulation of a polysulfide based material. The second strap was located at 180 degrees and was formed with fiber-reinforced adhesive screed over the strain sensors (Figure 2).

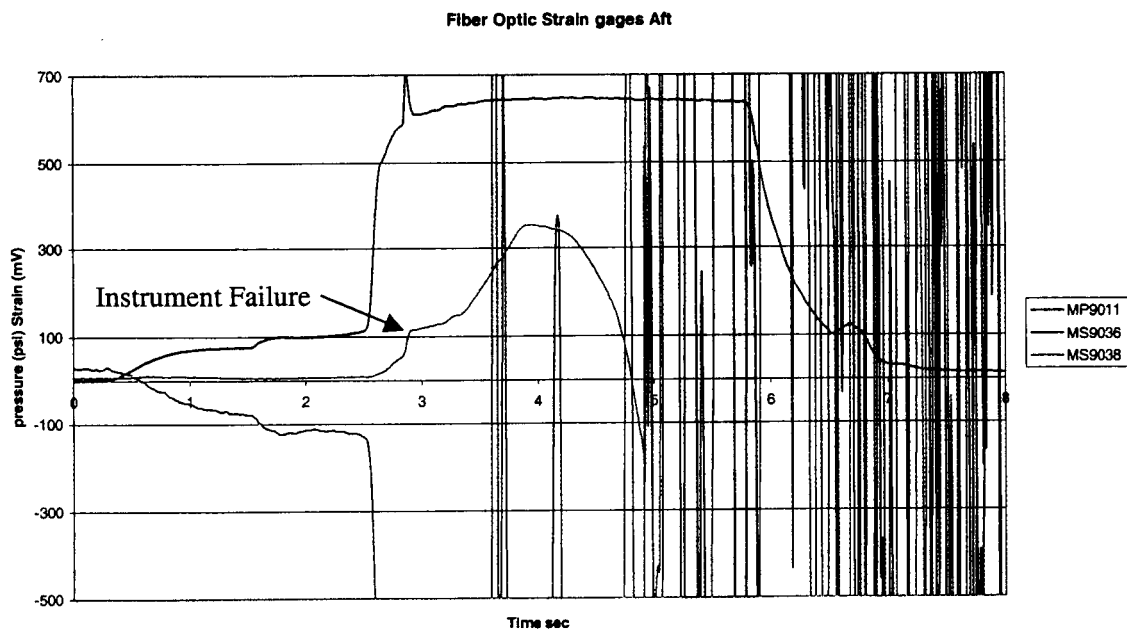


**Figure 2 Test 1 Instrumentation Locations**

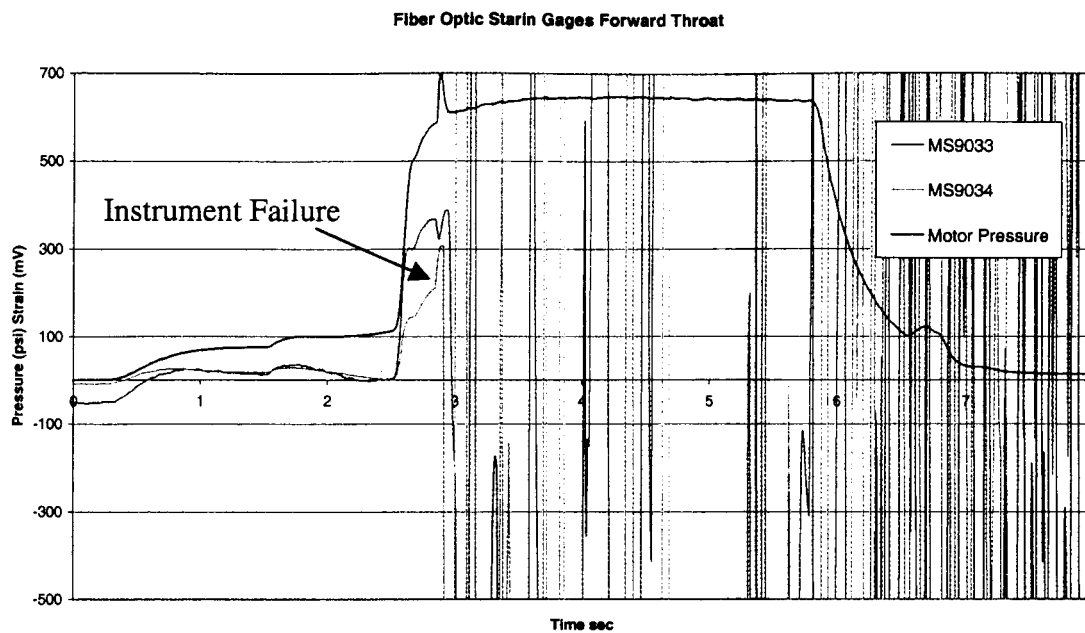
Both of the straps failed in the throat region of the nozzle. The reinforced adhesive survived slightly longer than the polysulfide and failed after about 0.4 seconds. The strain gages located downstream of the throat survived for approximately 1.5 seconds (Figures 3 thru 6). Because the throat region was obviously the first region to fail, additional analysis was put into developing a protection method that would survive there as well as the inlet and aft exit cone. The survival time through the throat was too short to acquire meaningful data but was an indication of the feasibility of the basic concept.



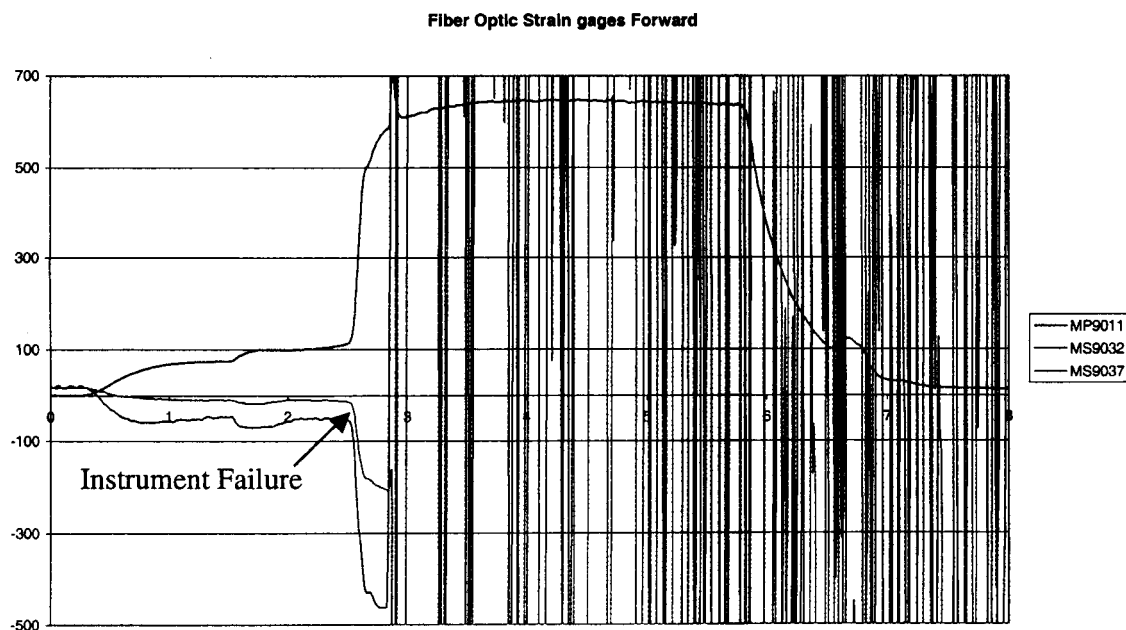
**Figure 3 Test 1 Instrumentation Aft of Throat at 180 Degrees**



**Figure 4 Test 1 Instrumentation Aft of Throat at 0 Degrees**

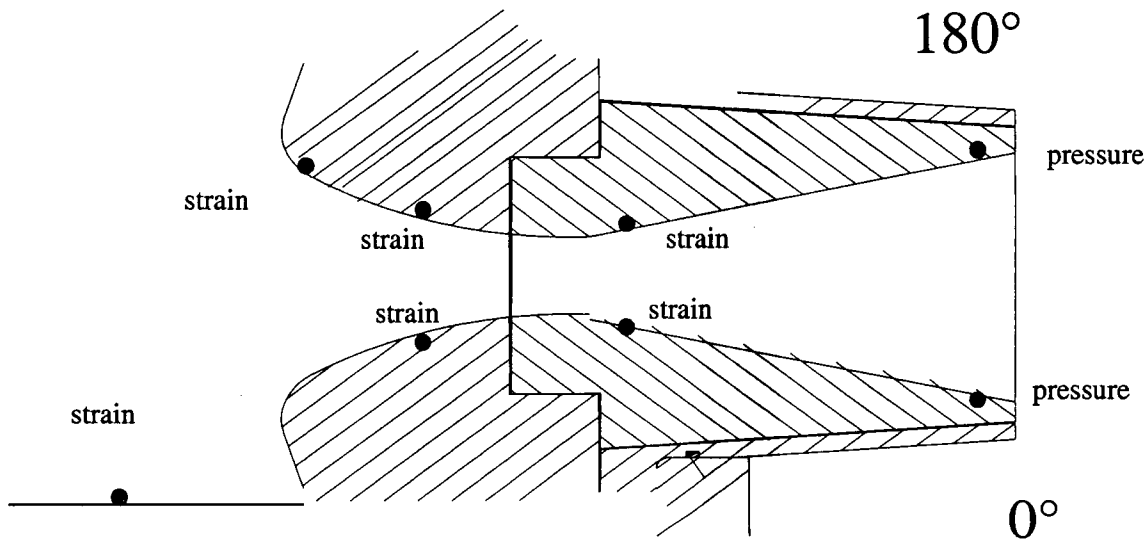


**Figure 5 Test 1 Instrumentation Forward of Throat at 180 Degrees**



**Figure 6 Test 1 Instrumentation Forward of Throat at 0 Degrees**

Test Two: The second test in the series utilized six fiber optic strain gages and two fiber optic pressure transducers. Instrumentation on the second test was installed in the nozzle the same as it was on the first test. This test also included a single strain sensor installed in the aft mixing chamber with an egress through the nozzle. A protective jumper strap of flexible material was utilized to make the transition from the aft mixing chamber to the nozzle inlet. The installation methods and materials used in this test were selected to increase the survival time through the throat region of the nozzle. The first strap utilized the adhesive material that gave the best performance in test one with an additional layer of carbon fiber cloth. The second strap was manufactured from a thin layer of composite material molded to conform to the nozzle contour and bonded with the adhesive used for the first strap. A fiber optic pressure transducer was added to the inlet of the nozzle under both straps. The pressure transducers were covered with a rubber disk which allowed the pressure to conduct to the sensor while protecting the gage (Figure 7).



**Figure 7 Test 2 Instrumentation Locations**

The improvements in the materials used for the second test allowed the straps to survive in the throat region for approximately 0.7 seconds (see Figures 8 thru 10). Unfortunately, the region of the nozzle selected for pressure transducer installation was in a region with little or no pressure changes and no significant data was obtained from these measurements. The protective jumper utilized to bridge the nozzle to aft sleeve joint performed well and proved the feasibility of bridging components in the internal motor environment with fiber optic instrumentation.

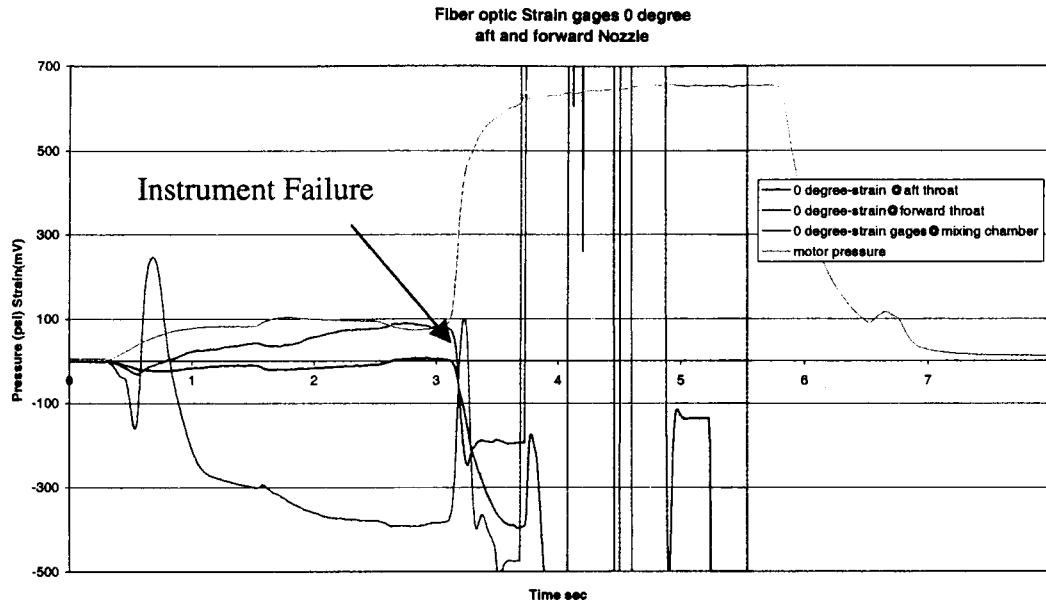


Figure 8 Test 2 Instrumentation on Nozzle at 0 Degrees

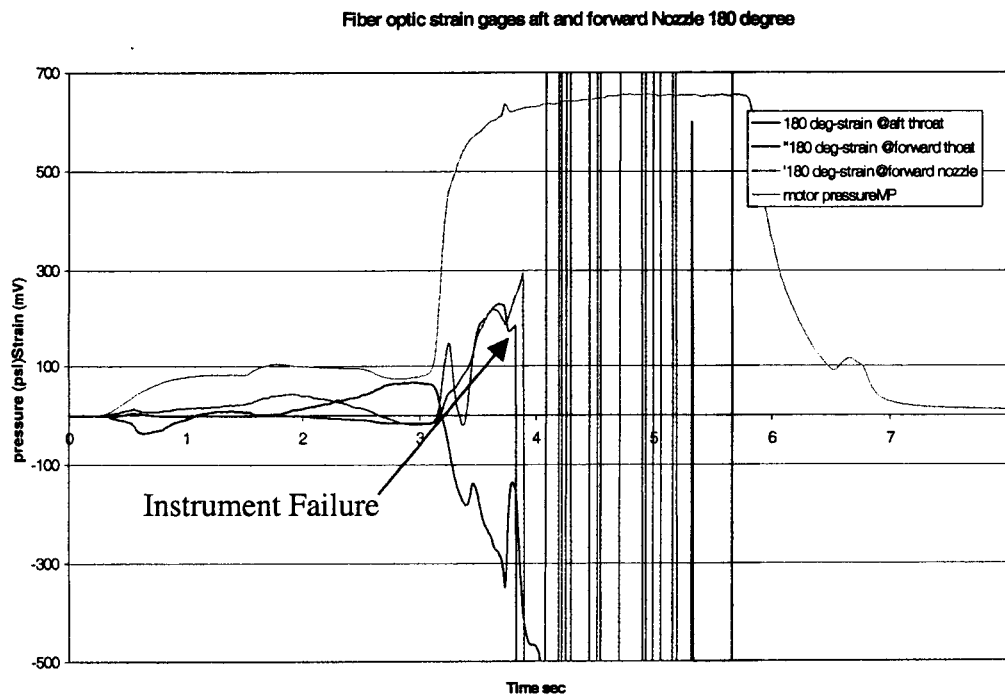
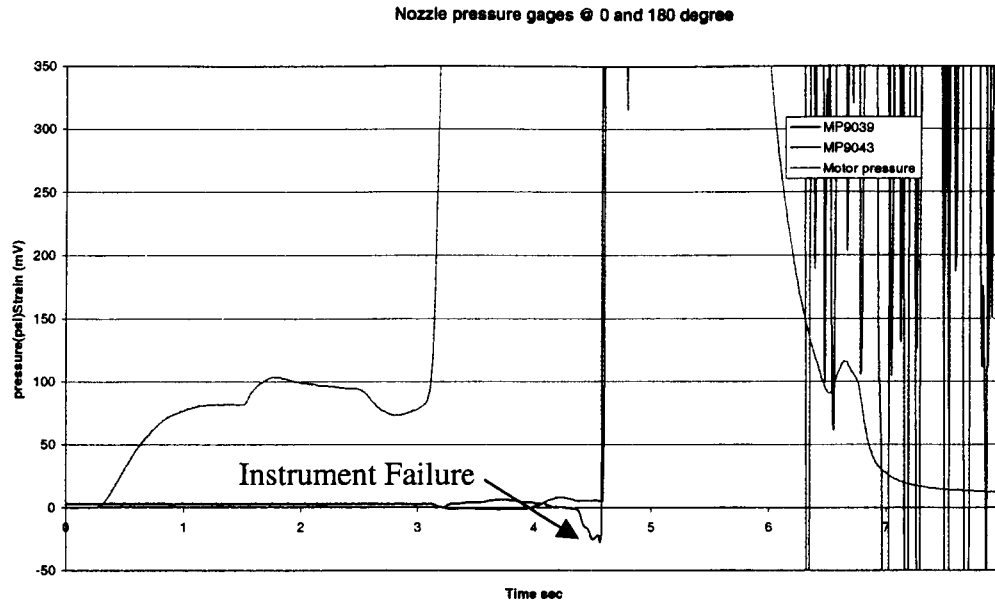


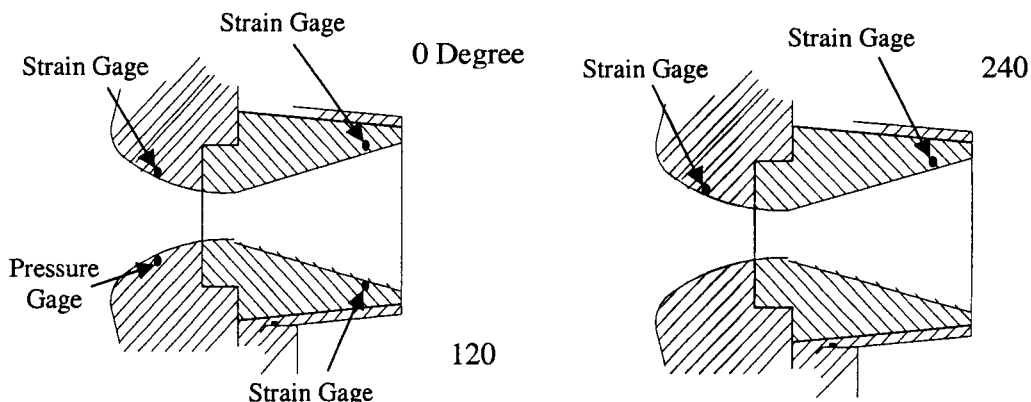
Figure 9 Test 2 Instrumentation on Nozzle at 180 Degrees



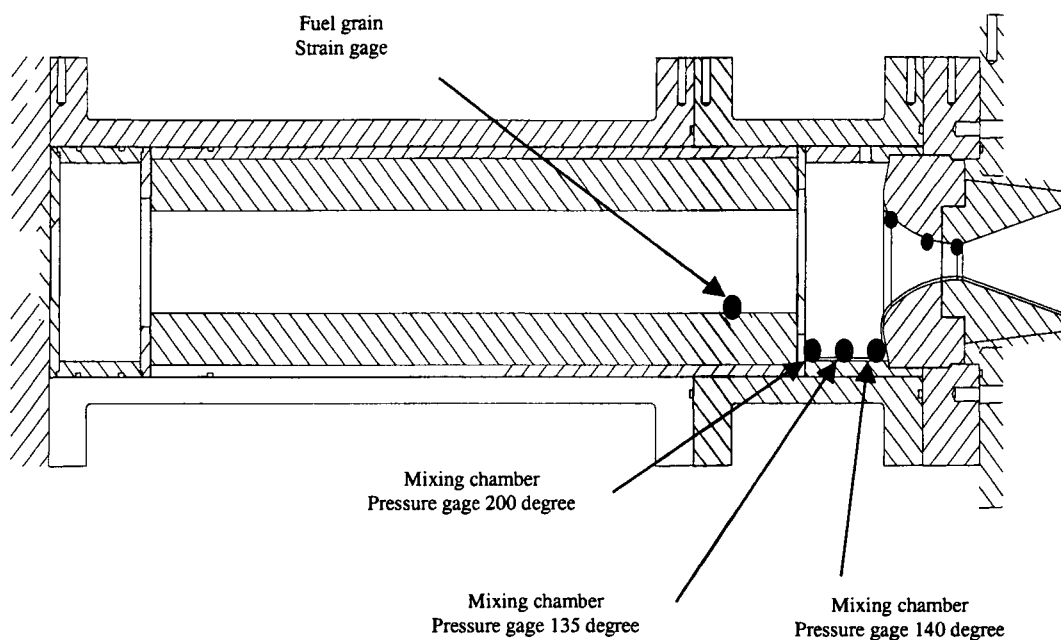


**Figure 10 Test 2 Pressure Gages on Nozzle**

Test Three: The fiber optic instrumentation in test three included six strain gages and four pressure transducers. The instrumentation in the nozzle was divided between three strap materials (Figure 11). The protective straps included two different composite materials bonded over the instrumentation at zero and one hundred twenty degrees. The instruments in the third location were protected with an elastomer material, which is manufactured with embedded carbon fiber strands. Strain sensors were bonded forward and aft of the throat in two of the three straps while the third strap included a pressure transducer forward of the throat and a strain sensor aft of the throat. Instrumentation in the aft mixing chamber consisted of three pressure transducers (Figure 12). Two of the pressure transducers were protected with a proprietary polysulfide based material and a rubber insulator protected the third. This test also included a fiber optic strain gage bonded to the fuel grain with the instrument lead connected to the aft sleeve with the same protective material tested in test two. The instrumentation in the aft sleeve and fuel grain exited the motor through a feed through and did not exit through the nozzle.

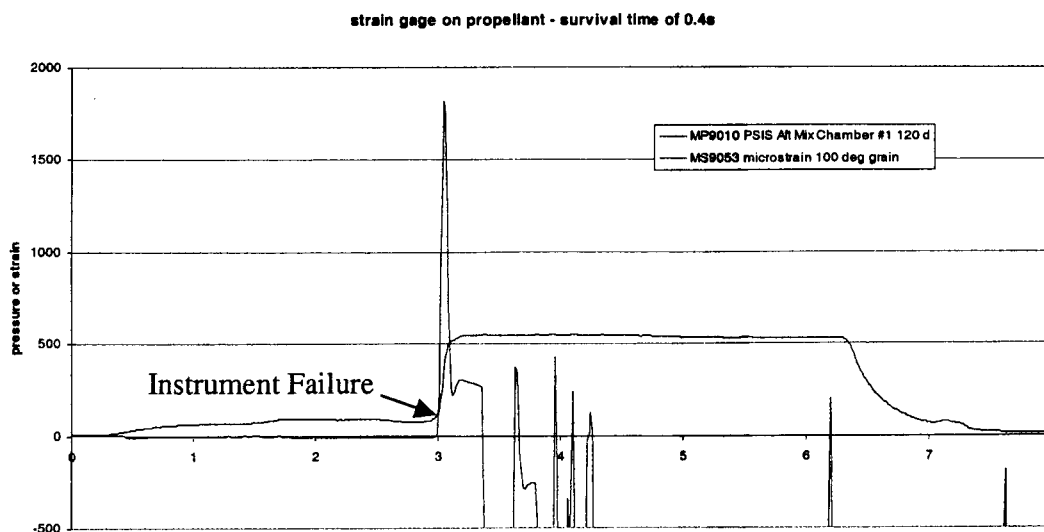


**Figure 11 Test 3 Instrumentation Locations on Nozzle**



**Figure 12 Test 3 Instrumentation Locations on Aft Sleeve and Fuel Grain**

The test results obtained from Test 3 (Figures 13 thru 18) indicated additional improvement in the survival time for the fiber optic instruments. The instruments in the nozzle throat protected by the carbon fiber reinforced elastomer functioned for the first full second of testing. All of the internal instrumentation routed through the feed through failed at 0.6 seconds. It was determined during the post-test inspection that the fibers were destroyed between the exterior of the phenolic aft sleeve and the feed through seal. This area is vented during the motor ignition and the fibers were not protected from the hot motor gases in this area. The fiber optic pressure transducer upstream of the nozzle throat provided good data for 0.8 seconds before the strap failed and the pressure sensors in the aft sleeve provided data comparable with the predicted values until the fibers failed at the feed through.



**Figure 13 Test 3 Fiber Optic Strain Gage on Fuel Grain**

0 deg data - survival times of 1.0 and 1.7 seconds

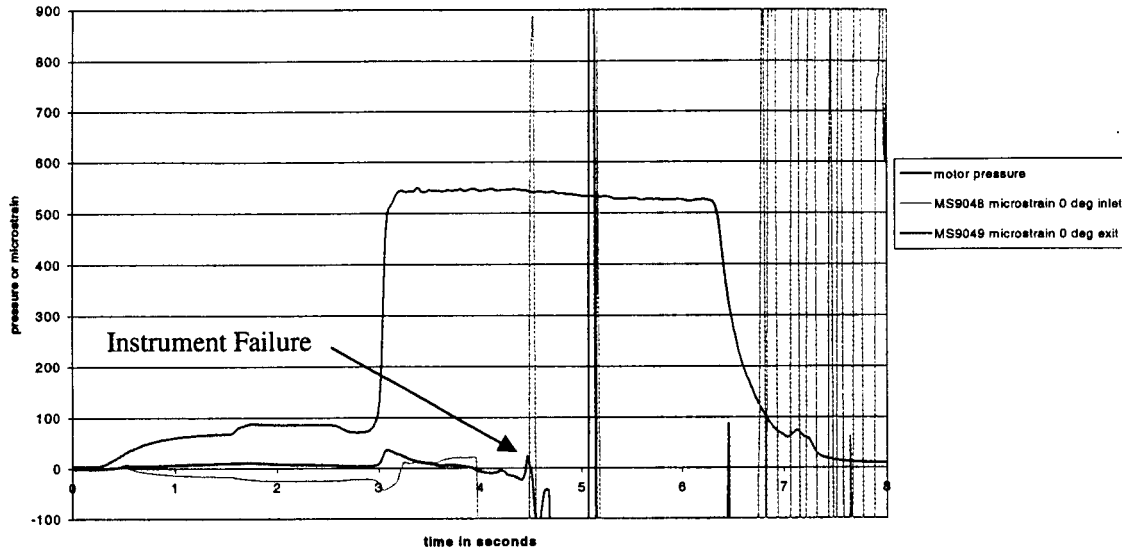


Figure 14 Test 3 Instruments on Nozzle at 0 Degrees

120 deg data - Survival times of 0.8 seconds

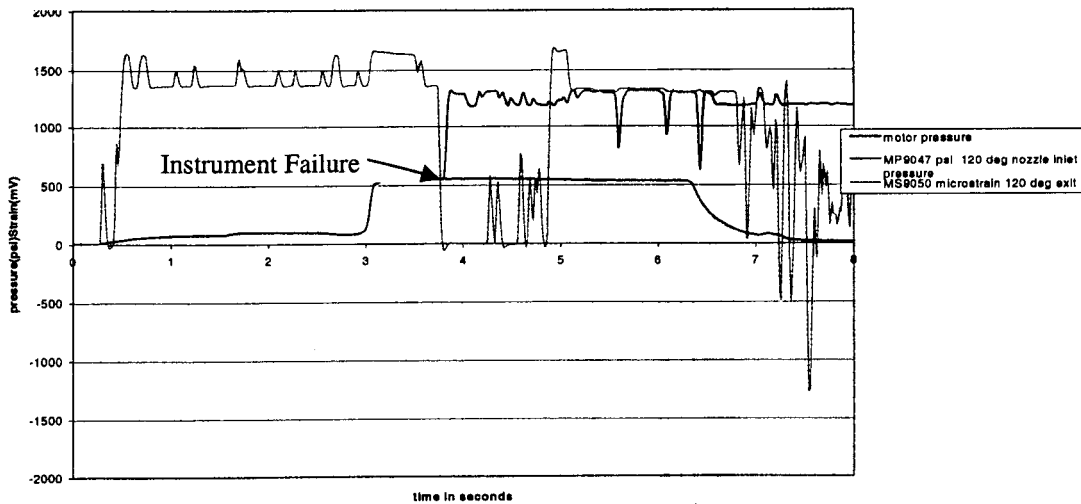


Figure 15 Test 3 Instruments on Nozzle at 120 Degrees

240 deg data -survival times of 1.05 and 2.2 seconds

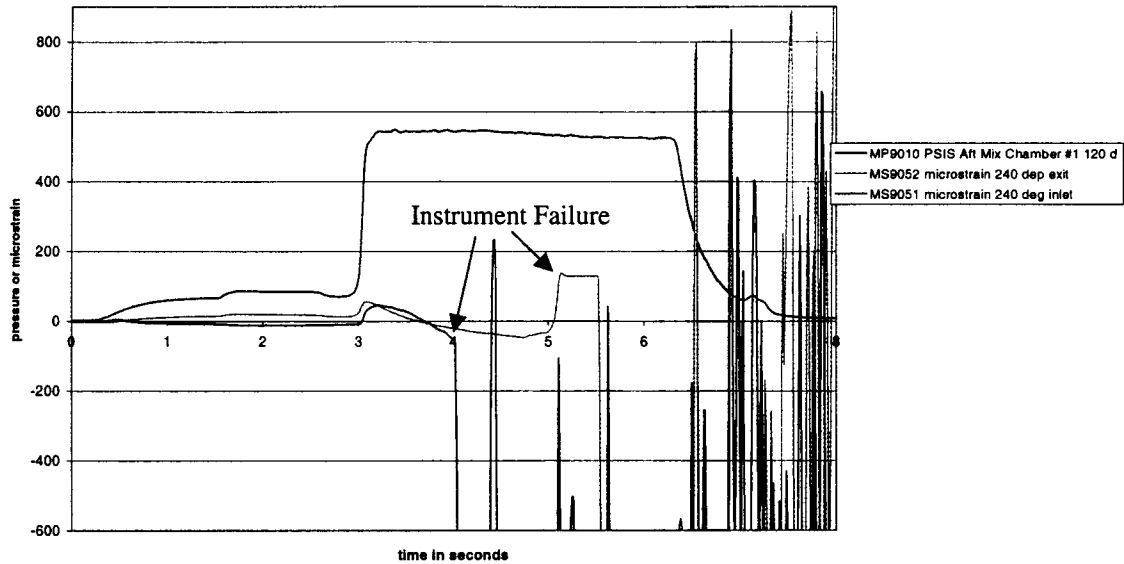


Figure 16 Test 3 Instruments on Nozzle at 240 Degrees

pressure - BUS channels; chamber survival time of 0.6s, inlet pressure = 0.8s

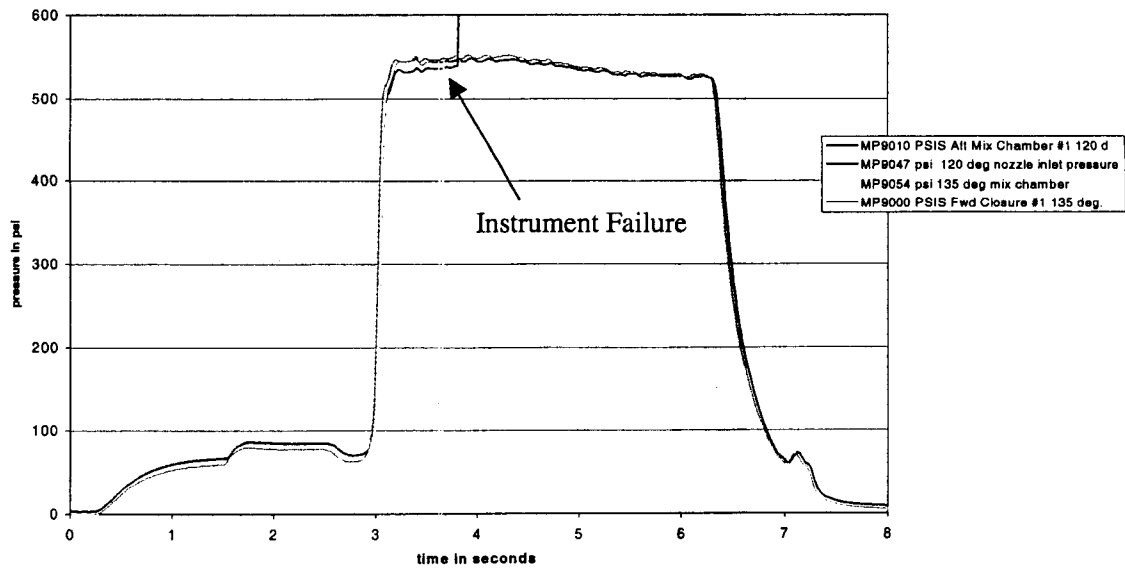
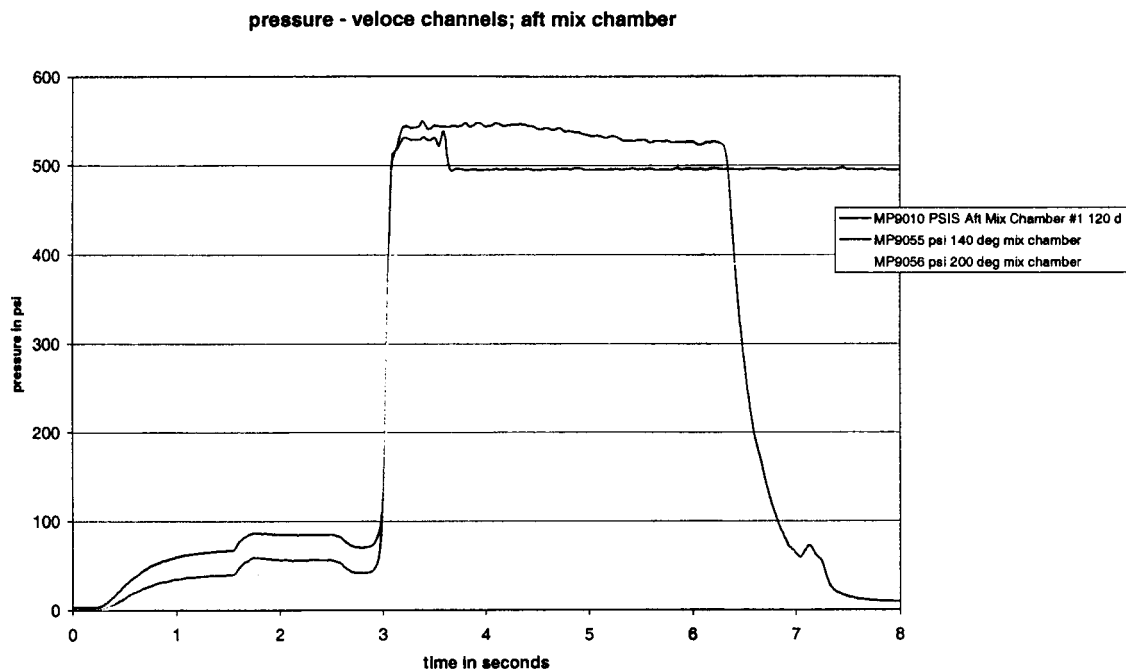
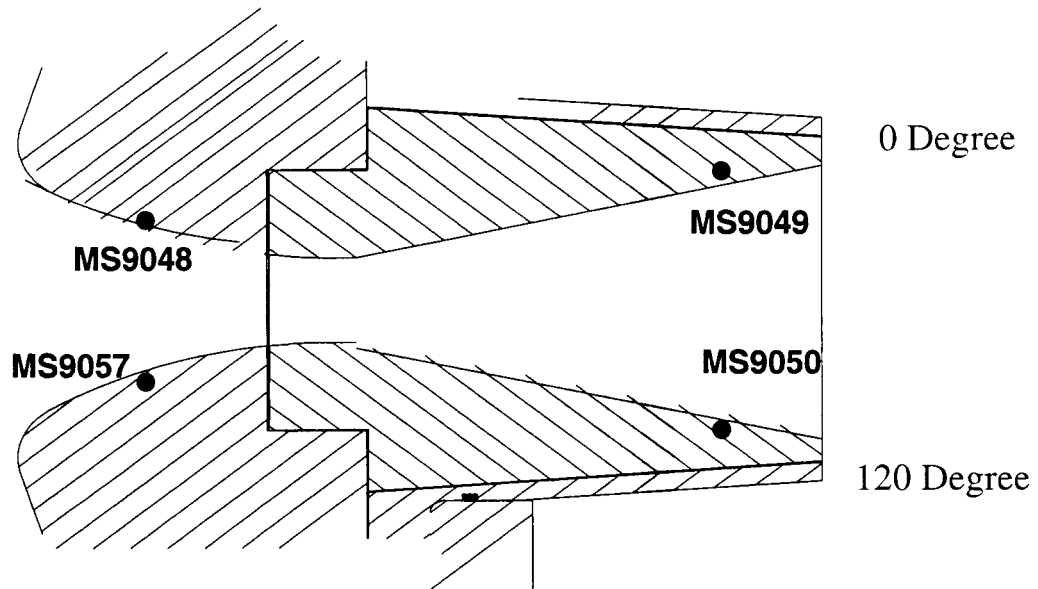


Figure 17 Test 3 Aft Mixing Chamber Fiber Optic Pressure Transducers

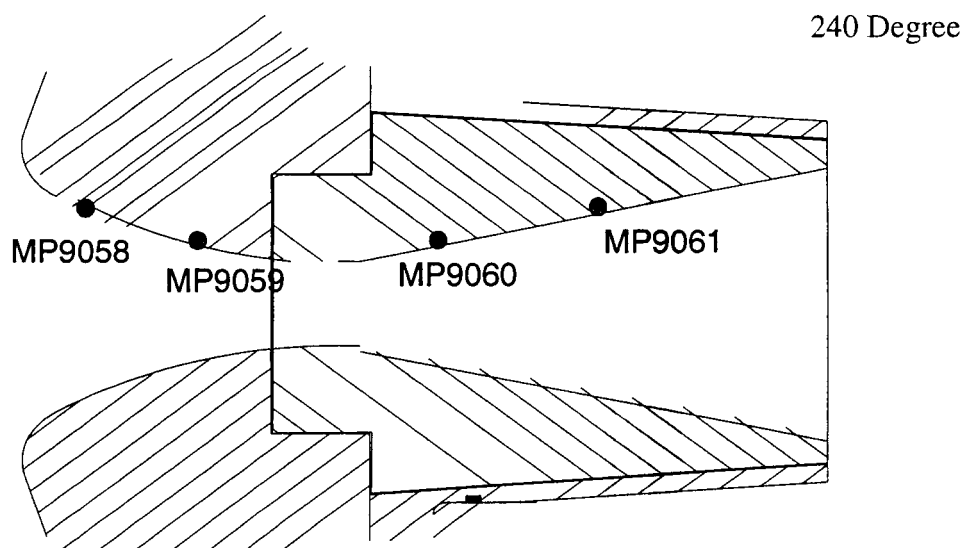


**Figure 18 Test 3 Fiber Optic Pressure Transducers in Aft Mixing Chamber**

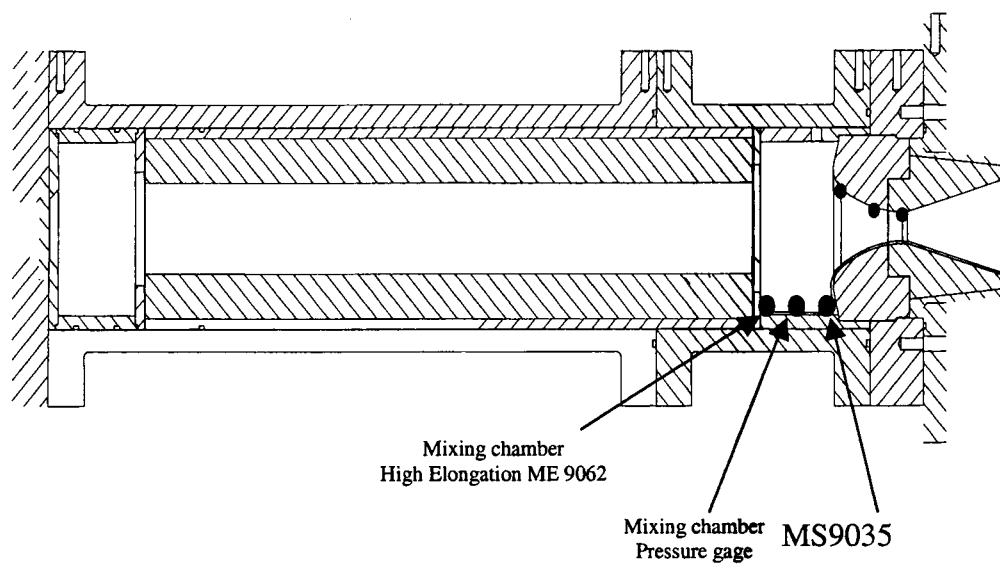
Test four: The fourth test in the motor series was instrumented with six fiber optic strain gages and seven fiber optic pressure transducers (Figures 19 thru 22). A high elongation strain gage was custom-built by FISO and tested in the aft sleeve. This gage was developed in an attempt to measure strain levels beyond the stress level normally allowed using a glass fiber instrument. Three protective straps were bonded into the nozzle. Two straps consisted of fiber optic strain gages before and after the throat region. One strap was formed with fiber-reinforced adhesive screed over the strain sensors. This method was tested during tests one and two. The second strap used the carbon fiber reinforced elastomer first tested during test three. A third strap of the reinforced elastomer was installed in the nozzle. This strap included two pressure transducers installed forward of the throat and two pressure transducers aft of the throat. Each transducer was installed with a protective rubber button over the gage to transfer the pressure load to the gage while protecting it from the hot motor gases. Six fiber optic instruments were installed internally in the motor in two different straps and routed out a feed through. A pressure transducer and two strain gages were installed on the aft fuel grain and attached to the aft sleeve with a protective jumper. The previously mentioned high elongation strain gage and a glass fiber gage were bonded to the aft sleeve as well as a pressure gage.



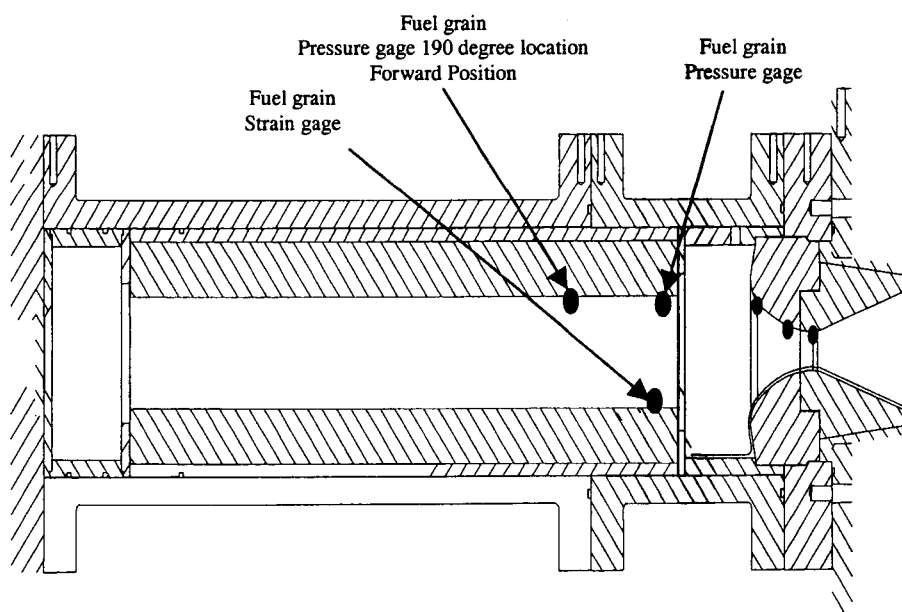
**Figure 19 Test 4 Instruments on Nozzle at 0 and 120 Degrees**



**Figure 20 Test 4 Instrumentation on Nozzle at 240 Degrees**

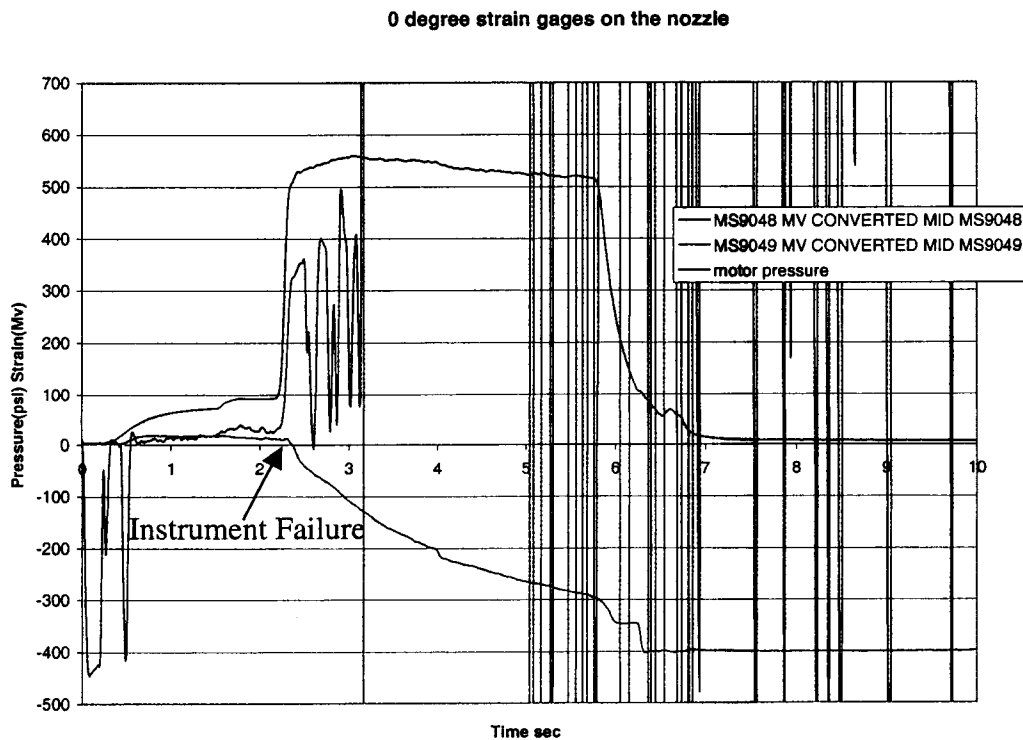


**Figure 21 Test 4 Instrumentation in Aft Sleeve**



**Figure 22 Test 4 Instrumentation on Aft Fuel Grain**

The data from test four indicated that the protection schemes were improved and allowed useful data to be acquired for 1.6 seconds through the nozzle throat using the carbon fiber reinforced elastomer. This met the test objective of developing a method of acquiring data for 1-2 seconds from instrumentation protected with a nozzle strap. The four pressure transducers bonded in the nozzle using the same material also performed well and provided results that compared favorably with the pressure predicted at those locations (Figures 23 thru 25). The instrumentation installed in the aft sleeve survived the entire 4-second test, which indicated that the improvements in the feed through protection methods were successful (Figure 26). Two of the three instruments installed on the propellant bore were damaged prior to test but the remaining pressure transducer provided accurate pressure data for 2.3 seconds (Figures 27 and 28). The damage to the instruments in the bore probably occurred outside of the test motor in the splices between the feed through and the data system. Mechanical splices were utilized and proved to be unreliable during motor transportation and instrumentation hookup in the test area.





strain gages at 120 degree on the nozzle

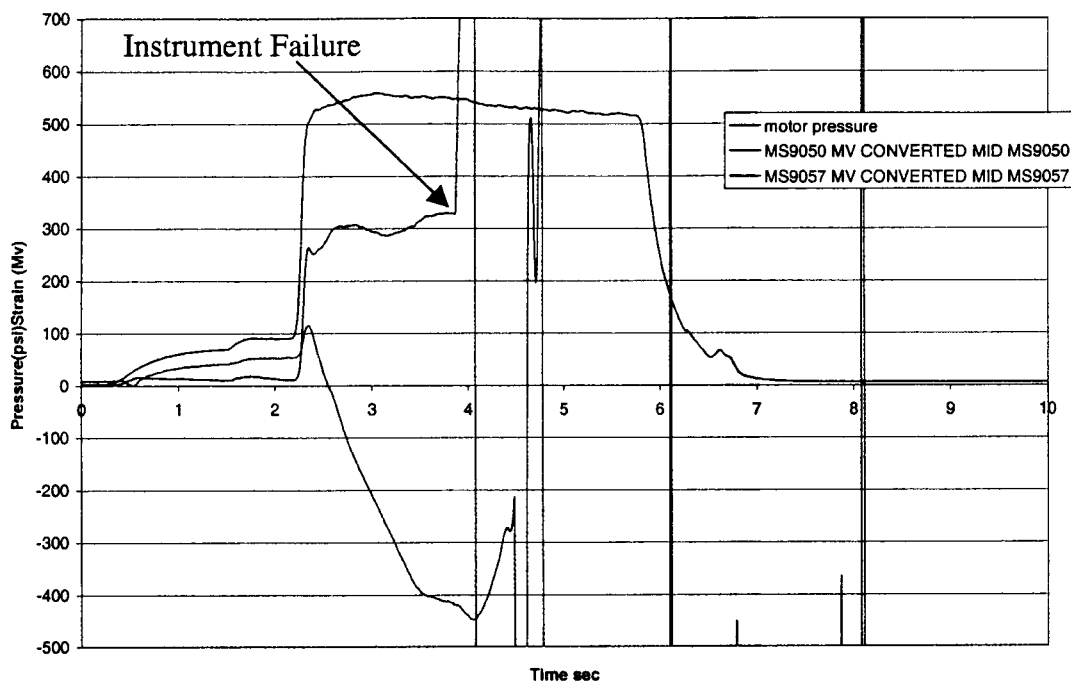


Figure 24 Test 4 Instrumentation on Nozzle at 120 Degrees

pressure belt @240 degree

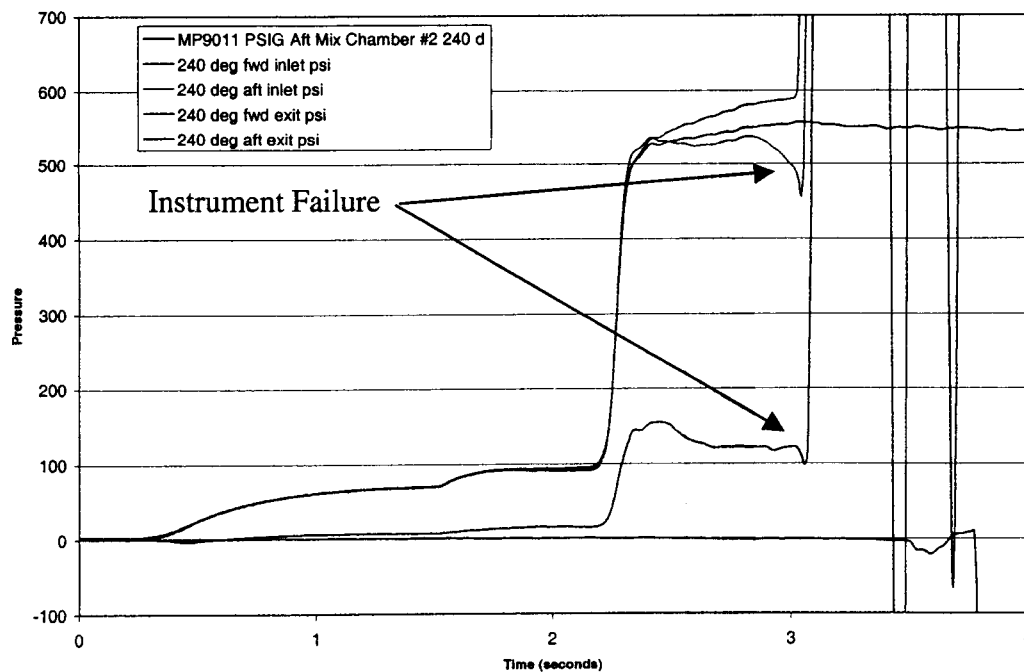
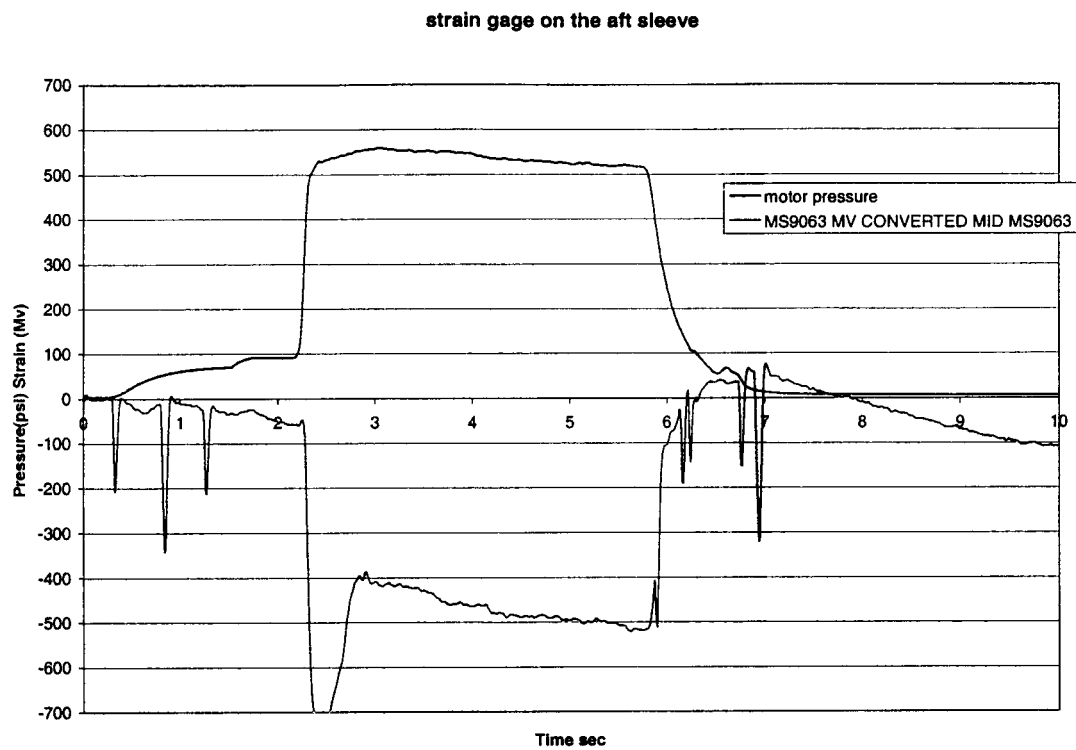
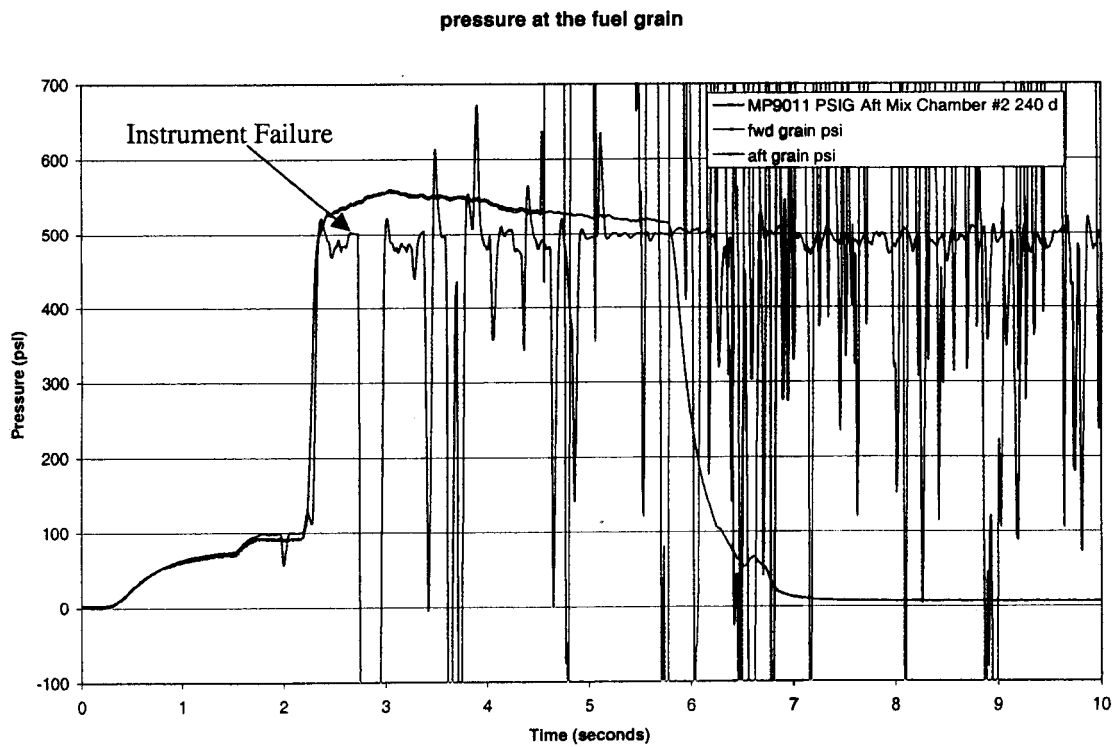


Figure 25 Test 4 Instrumentation on Nozzle at 240 Degrees



**Figure 26 Test 4 Strain Gage Installed on Aft Sleeve**



**Figure 27 Test 4 Pressure Transducer Installed on Fuel Grain**

strain gage on the fuel grain

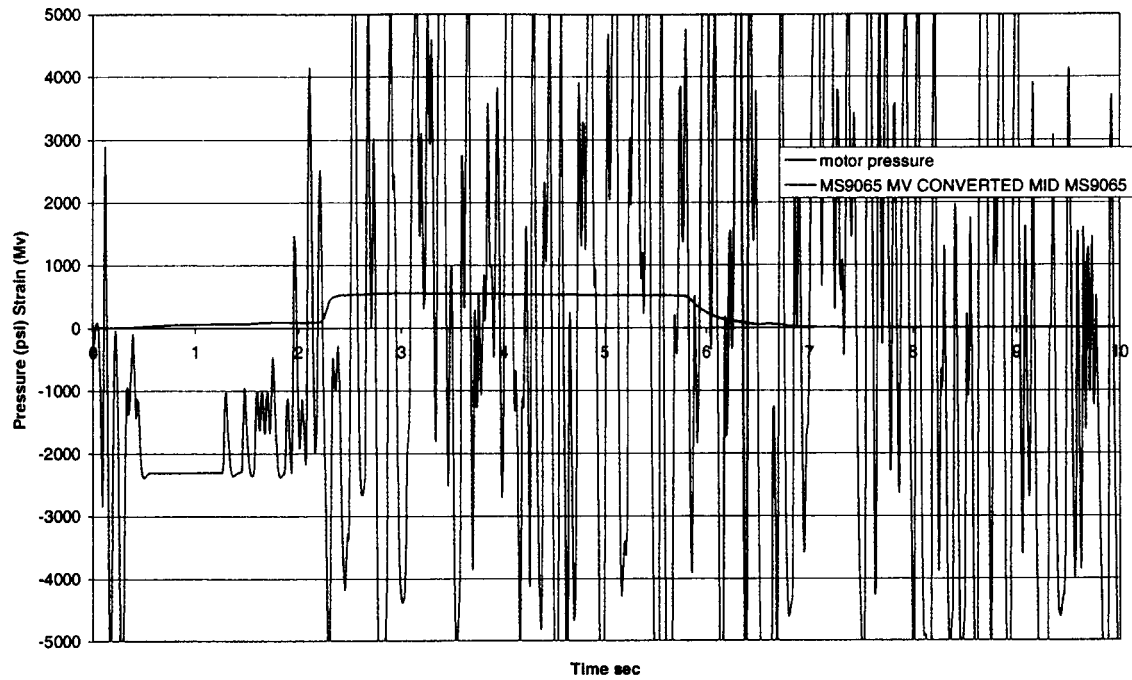


Figure 28 Test 4 Fiber Optic Strain Gage Installed on Fuel Grain

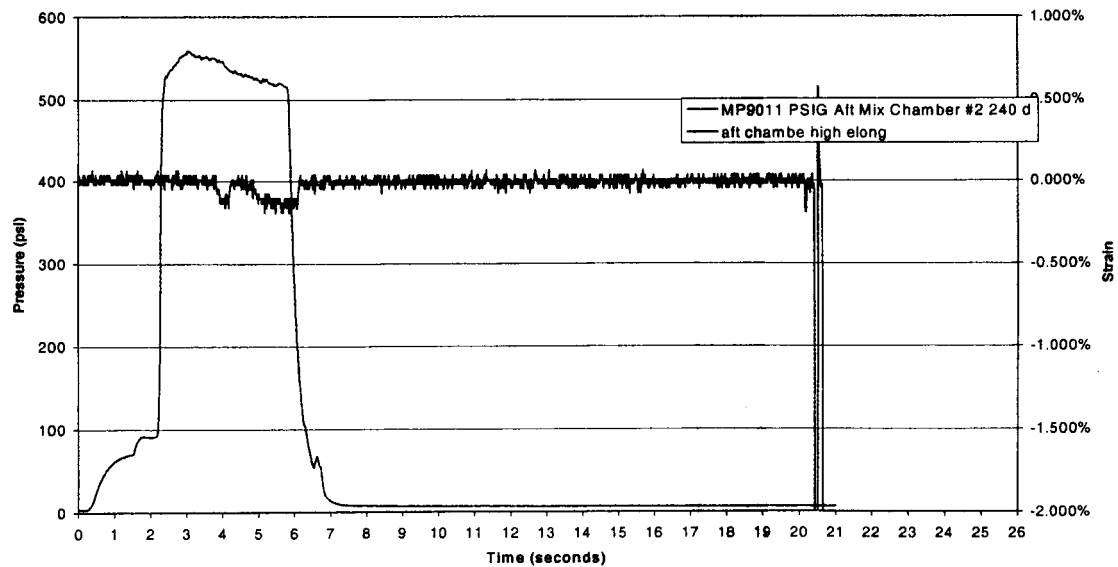
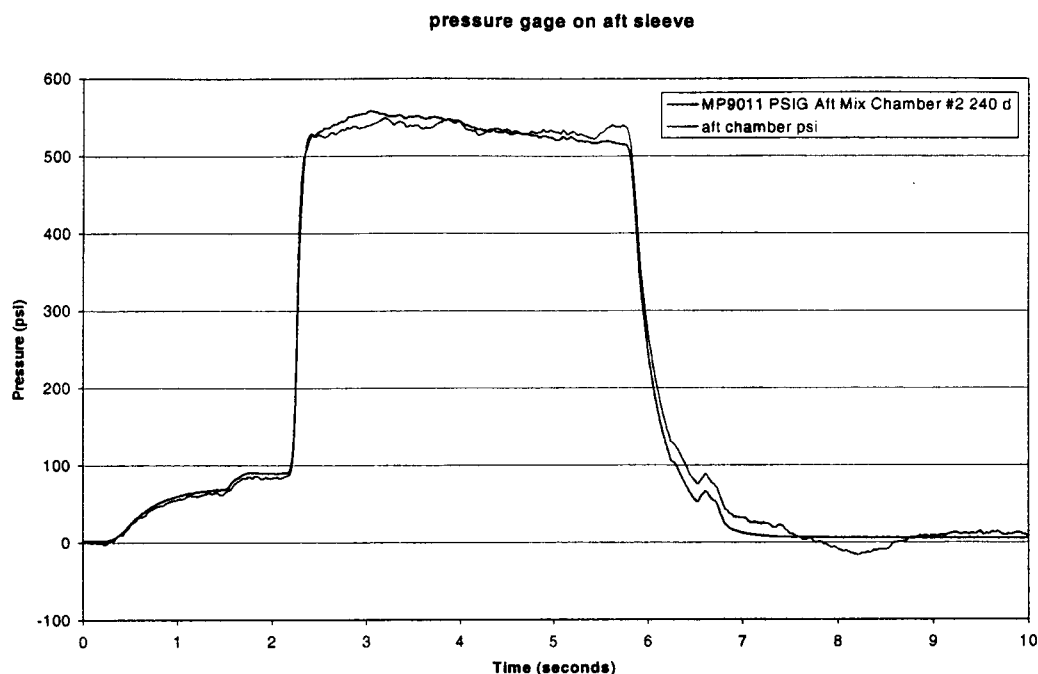


Figure 29 Test 4 High Elongation Gage Installed on Aft Sleeve



**Figure 30 Test 4 Comparison of Fiber Optic and Conventional Pressure Transducer**

### Conclusions

Fiber optic instrumentation has distinct advantages over conventional instrumentation for applications in solid rocket motor testing. They are small, have low mass, require no excitation voltage and they are virtually immune to typical noise and electro-magnetic interference. This type of instrumentation has not been utilized in SRM testing due to the extreme environment typically encountered. A series of tests utilizing a hybrid rocket motor test bed was conducted to develop protection schemes that will allow the fiber optic instruments to survive the internal SRM environment. The goal of this testing was to allow sacrificial instrumentation to survive for 1-2 seconds and acquire data during the ignition transient event. Several protective materials were tested and improvements in the survivability times increased as testing progressed. Survivability times of 1.6 seconds through the nozzle throat were obtained from candidate materials. Straps of elastomers with fiber optic instruments were bonded onto the fuel grains, which allowed propellant properties and bore pressures to be acquired for up to 2.3 seconds. Installation techniques, including jumpers and feed through seals, were improved to allow optical fibers to be routed out to the signal conditioning and data systems.

It has been demonstrated, during this series of test motors, that fiber optic instrumentation can be utilized in the solid rocket motor environment to make accurate measurements during a short event such as motor ignition or pressurization. The apparent key to applying this technology is in developing a method of protecting the fiber optic instruments and the connecting fibers for the test duration. The duration of usable data will be dependent on the area of interest and the method of motor egress. Successful application of the techniques outlined in this paper could prove to be useful in developing protection methods for other SRM test beds or test beds with similar high temperature gas environments.